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ASSESSMENT OF THE PRACTICAL POTENTIAL OF MATHEMATICAL MODELLING OF FLUIDIZED BED COMBUSTION AND RECOMMENDATIONS FOR CANADIAN PARTICIPATION IN IEA JOINT PROJECTS ON MODELLING

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Preface

This is the Final Report on work performed under a contract with Supply and Services Canada:

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Summary

A brief survey of the nature, applications, and present state of the mathematical modelling of fluidized bed combustion (FBC) is given. The near-term potential of such modelling as a tool for designing commercial FBC boilers and combustors is assessed. Finally, recommendations are made concerning Canadian participation in international joint research projects on FBC modelling organized under the International Energy Agency. It is concluded that modelling is already a cost-effective tool for design provided that qualified people are employed for its application. Collaboration in IEA joint projects could bring considerable benefits, but the decision to participate should be based on specific, well thought-out proposals.

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1. Introduction

This report has been prepared for Energy, Mines and Resources Canada as part of the work undertaken under the contract specified on the title page. The contract required the author (the Principal Investigator) to attend the 7th Combined Technical and Executive Committee Meeting of the IEA [International Energy Agency] Implementing Agreement for Cooperation in the Field of Atmospheric Fluidized Bed Combustion in Industrial or District Heating Boilers. The meeting took place in Pisa and Naples, 4--7 October 1983. In accordance with the contract, the author presented a paper on Canadian work [Xu, et al. 1983], heard and assessed the other papers presented, and participated on behalf of Canada in discussions on the merit and nature of possible joint projects on mathematical modelling which might be pursued under the IEA Agreement. The present report addresses the final requirements of the contract (the fifth and final task in the Statement of Work): to prepare a report including

- a brief review of all papers on mathematical modelling presented at the IEA Committee meeting
- an assessment of the near-term potential mathematical modelling is likely to have as a cost-effective tool in designing commercial fluidized-bed combustors and boilers
- a reasoned recommendation as to whether Canadian participation in any further joint project on mathematical modelling of fluidized-bed combustion is likely to be justified in terms of benefits to Canadian suppliers and users of the technology

Because of the difference in subject matter and interest, the review of papers presented at the IEA Committee technical meeting has been relegated to a separate, informal report.

The Committee meetings were chaired by Mr. F.D. Friedrich, the Scientific Authority for the subject contract. Mr. Friedrich raised a list of questions which served as an agenda for the discussions following the papers.

1. If we had models, what would we do with them? Answers to this, some raised at the meeting and others added by me, are given in Sect. 2.2 herein.

2. Do we see a possibility of developing reasonably accurate and fairly complete models? The consensus was, yes. The following supplementary questions were put:

(a) Is there agreement on a general one-dimensional (1-D) model? The discussions indicated that agreement, among those at the meeting and among researchers generally, is significantly incomplete. An assessment of 1-D modelling is given in Sect. 3.3.

(b) What are the submodels? The list, with additions by me, is given in Sect. 3.2.

(c) What are the special interests of the IEA Committee participants in the various submodels? Are any not covered? These questions were inconclusively pursued. It appears that some of the submodels are well covered, but there is not presently anyone who is engaged in a full-scale integrative effort.

(d) What are the important three-dimensional (3-D) effects? How shall these be dealt with? These questions are considered in Sect. 3.4.

3. In what areas of modelling has good progress been made? The discussion on this at the meeting wandered considerably and

came to no clear conclusion, but many opinions were submitted. My impressions, partly reflecting my own judgment, are given in Sects. 3.3 and 3.4.

4. In what areas of modelling is work most needed? A number of the most active researchers submitted their favourite candidates:

- [] freeboard reaction
- [] combustion of gas and solids in the splash zone
- [] measurement techniques
- [] particle dispersion and macro-circulation patterns
- [] particle/surrounding heat and mass transfer in the bed [for burning coal particles], especially the Sherwood number

My own assessment is given in Sects. 3.3 and 3.4.

5. Can the needed work be accomplished better or more quickly by cooperation? The consensus was, quite strongly yes. Forms of cooperation mentioned were:

- [] share ideas
- [] share data
- [] share plans, experimental designs
- [] submit experimental [research] plans for review and suggestions

My recommendations on this are given in Sect. 5.

6. What should be done as cooperation in the next year? The

following possibilities were offered by Mr. Olsen:

- ☐ meetings, to exchange information
- ☐ joint work in certain areas, e.g., instrumentation
- ☐ cooperation in a specific project
- ☐ exchange of personnel
- ☐ exchange of plans for new research programs
- ☐ develop a common integrative model, with various participants working on the shapening of submodels

My recommendations for short-term cooperation are given in Sec. 5.

In what follows, certain specific questions are considered as indicated above. However, I have not bound the discussion to the IEA Committee meeting but have aimed to arrive at a reasoned general assessment of the present state and near-term potential of FBC modelling, as contractually specified. This assessment leads to my recommendations for Canadian involvement in the IEA cooperation, Sect. 5.

It should be noted that the IEA Committee meeting only considered one type of modelling, herein called distributed parameter modelling. There is however a complementary kind of modelling, called lumped parameter modelling, which is equally important in practice. Both types of modelling are discussed herein, as are their roles in theory and practice.

2. General considerations regarding modelling of FBC

2.1 Broad categories of models

There are two broad classes of mathematical models that

may be employed to describe systems such as FBC combustors or boilers:

1. Distributed parameter models (DPM's). These are based on physically detailed, strongly deterministic mathematical simulation. Their use amounts to running experiments on a computer instead of a physical system, and similar data (one might say "simulated data") are generated.

2. Lumped parameter models (LPM's). These are based on analysis of the data provided by distributed parameter models and/or physical experiments. The results are typically "correlations" expressing generalizations about interesting aspects of the system response, presented in graphical or equation form.

In the simplest problems, the DPM is analytically solvable and the LPM's of interest are analytically derivable from that solution. In a process as complex as FBC, however, whatever correlations exist are not normally explicitly and uniquely determined by a DPM; instead, they must be hunted for with the help of order-of-magnitude analysis, physical reasoning, intuition, and statistical analysis. The solution of the DPM in such cases can only be managed numerically, and the output consists entirely of sets of numbers just like data generated by an experiment. Any LPM that may be found expresses a conspicuous degree of systematic behaviour (a trend or correlation). Such LPM's are typically imperfect and semi-statistical, having an inherent degree of uncertainty. Physically, this means that while many factors may affect a given aspect of behaviour, they are unlikely to all be important at once. A "correlation" dwells on the linkages between an output variable of interest and those inputs that are most influential in a given operating regime. The uncertainty is due largely to the weakly influential inputs which are ignored.

A very good DPM may predict system performance well for any given operating conditions and still be quite unrevealing of general trends; one is, in the first instance, simply comparing numbers with numbers, and the difficulty is that of recognising a structured forest in the trees. An LPM may interestingly and usefully represent trends over the explored range of conditions, but care must usually be taken not to extrapolate too far when using the model for prediction. Implications of scaleup, transients in operating conditions, and control characteristics may be evident in an LPM but virtually invisible in a DPM.

The theoretically most attractive way of proceeding in modelling is to develop a very good DPM, use it in place of experiment to generate simulated operating data, and then to analyze these data and hopefully formulate some useful LPM's. An example from aerodynamics illustrates the point: boundary-layer theory (the DPM) can be used to accurately predict the stress distribution over the surface of a dirigible. These data can be used to compute the drag coefficient C_D which is then represented as a function of the Reynolds number Re (the LPM). The C_D--Re correlation reveals the most interesting general trends and also indicates the effects of scaleup. Because the basic data are easily generated from the DPM by computer, expensive and time consuming physical experimentation is avoided. However, one is not always so lucky, and in the worst cases it is commonly found that physical experimentation is the only means of getting reliable data.

In the modelling of FBC we have grounds for optimism that useful DPM's can be developed so that much, if not all, of bench-scale and pilot-scale experimentation may be rendered unnecessary. However, there are also still considerable problems remaining and it may be that DPM's, though very useful, will never attain the desired high accuracy and versatility.

2.2 Uses of models

The principal uses of models and modelling, some of which have been alluded to above, are:

1. As a vehicle for learning, to gain understanding of the FBC process.

2. To guide experimentation.

3. To predict as exactly as possible the performance of a given system under given steady-state operating conditions.

4. To determine how steady-state performance is affected by changes in operating conditions.

5. To predict dynamic response in various situations, as in startup, shutdown, and in-run changes of conditions. The last may involve changes of load (load following), changes of feedrate and feed characteristics (coal, limestone, excess air), change of recycle, fouling or other deterioration of heat transfer systems, etc.

6. To guide scaleup.

7. As a tool for process and equipment design. Ideally, the model should be sufficient by itself. In practice, it may have to be supplemented by bench-scale and pilot-plant work.

8. As a tool in equipment and process evaluation and optimization, including economics.

9. As a tool in process control schemes.

These uses obviously overlap in various ways, but each constitutes a distinct aim. It may be noted that DPM's serve

uses 1--8, LPM's are helpful for all uses, LPM's are especially helpful for uses 4--9, and LPM's are virtually necessary for use 9 (DPM's are far too complex and cumbersome for any reasonable on-line process control strategy).

3. Distributed parameter models for FBC

3.1 Structure of DPM's

Distributed parameter models for FBC, as for most complex processes, involve a hierarchy of integrative or master models and sub-models. The integrative models are of the kind often referred to as governing equations: they are typically material, energy and momentum balances, in the form of differentio-integral equations or their finite-difference renditions, and they apply at all points in the system or at least over major parts. There is relatively little argument about the general structure of these equations. However, they typically contain many terms for which sub-models must be supplied that involve detailed assumptions about the mechanisms of phenomena. It is at the level of these sub-models that most uncertainty, dispute, and ignorance occurs.

3.2 Submodels

Following is a list of submodels entering the distributed-parameter modelling of FBC:

- fluidization dynamics models

1. Division of gas flow between dense phase ("emulsion") and dilute phase (jets, channels, bubbles, slugs). Component models:

   (a) The neighbourhood of the distributor where the mode of introduction of the gas is influential and the dilute phase may initially be of jet-like character

(b) The normally major portion of the bed, involving bubbling, bubble-coagulation, slugging, and sometimes turbulent fluidization

(c) The bed-freeboard transition zone (the "splash zone")

2. Exchange of material and energy in the gas between the dense and dilute phases. Particularly important is the transfer of oxygen from the dilute phase to the dense phase.

3. Solids (particle) mixing in the bed by processes of dispersion ("diffusion") and streaming ("circulation" or "bulk flow"). Particularly important is the movement of coal.

□ coal reaction in bed

4. Devolatilization

5. Fragmentation (breaking apart into smaller particles, particularly during devolatilization).

6. Attrition (wearing down, generating fines, by abrasion)

7. Volatiles combustion

8. Char combustion

□ limestone reaction in bed

9. Calcination

10. Sulphation

11. Attrition

- ☐ fines transport, with and without recycle of elutriated particles

12. Particle concentrations and fluxes in the transport disengagement zone (where the larger particles ejected from the bed fall back in)

13. Elutriation (dust transport out of the combustor, to be caught in cyclone and baghouse). Particularly important is combustible matter (char particles)

14. Residence time of elutriable particles in bed and freeboard, particularly char

- ☐ freeboard ractions

15. Char burning

16. Carbon monoxide burning

17. Devolatilization and volatiles burning (mainly with overbed feeding)

18. Sulphation/desulphation of sorbent particles

19. NO_x/char reaction

- ☐ heat transfer

20. Bed to tubes

21. Bed to cooled walls

3.3 One-dimensional DPM's

Reasonable success in full modelling of FBC by distributed parameter models has so far been achieved only in the case of essentially one-dimensional (1--D) models. This is the ideal case in which coal, limestone, air and recycled solids are fed in such a way and heat transfer surfaces are so disposed that lateral non-uniformities are unimportant. The master or integrative models (full material and energy balances; see first paragraph of Sect. 3.1) are then 1--D, involving only height above the distributor. Most pilot-plant and bench-scale systems under 0.5 m dia. operate in a predominantly 1--D manner and are usually treated as fully 1--D in DPM modelling. In systems with beds of large cross-sectional area, essentially 1--D behaviour in combustion and sulphur capture is normally desired, too, when the full bed area is being utilized (or over that part of the bed, the unslumped portion, which is in use). To this end, feedpoints for air, coal limestone, and recycle solids are usually made appropriately numerous and uniform in distribution. Some significant 3--D effects and related considerations are discussed in the next section. The remainder of this section concerns the current status of 1--D modelling and related experimental studies.

The classical example of the application of fluidized bed reactor technology is in catalytic cracking. The bed particle diameters there are however typically small (ca. 50 μm), fluidizing velocities are correspondingly low, and operation is in the so-called fast bubble regime. In atmospheric fluidized bed combustion, bed particles are typically around 1 mm dia. and fluidizing velocities are relatively high. Operation ranges over the transition from fast bubble to slow bubble regimes, and also involves slugging and turbulent fluidization. Use of high fluidizing velocities is necessary in order to get interestingly high rates of combustion (MW heat release per unit of bed cross-sectional area). Large particles must accordingly be used in

order not to blow away the bed in operation without bed recirculation. Experimental study and modelling of systems in the fast bubble regime (with small particles and low fluidizing velocity), as a result of long work in catalytic cracking and other processes carried on in the same regime, is in a fairly advanced and strong state, though by no means complete. The regimes of interest in FBC, however, are relatively poorly understood and quantitative treatment is in considerably weaker condition. The presence of in-bed heat transfer tubes in FBC introduces another complication. Most modellers have ignored the differences and have tried to model bed dynamics and transfer processes by the bubbling-bed models familiar from study of catalytic cracking. A considerable number of experimentalists, particularly in bench-scale studies but also some in pilot-scale studies, have employed sand-beds of unrealistically fine sand in studies of FBC, again pushing conditions toward the familiar but away from the practical.

There is, thus, a need to arrive at an understanding and treatment of FBC bed behaviour as it actually exists under practical FBC conditions. Experimental work of whatever kind should be carried out with appropriate bed material. Some investigators have been following these guidelines but many others haven't. The result has been confusion, people purportedly talking about the same thing but actually addressing significantly different problems.

More, and more careful, work on bed dynamics and transfer processes would improve understanding of mechanisms and add to the detail and accuracy of models. It appears that the two-phase model of fluidization is acceptable up to the fast fluidization regime (the regime employed with recirculating beds). Improved knowledge is needed of:

- gas-phase material transfer coefficients between the dense and dilute phases

- the mean upward component of gas velocity in the dense phase. It is presently usually assumed that the gas flow in the dense phase is at the minimum bubbling velocity

- processes in the near region of the distributor where gas distribution is uneven and initial special structures such as jets may be found

- processes in the terminal region of the bed--the splash zone--where special behaviour again occurs

- particle movement in the bed, particularly in the dense phase, by dispersion and circulation, in the presence of in-bed heat transfer tubes.

All the areas mentioned have had considerable study but in no case can it be said that qualitative or quantitative understanding in relation to FBC is good; it is at best between vague and fair.

However, here and in all aspects, it must be asked, "To what extent is detailed knowledge and accurate description of any given phenomenon, or class of phenomena, really necessary to the correlation and prediction of the important performance parameters?" In this vein, we have strong evidence [Xu, et al. 1983] that elutriation is virtually independent of bed height and depends in a very simple way on particle diameter and fluidizing velocity. It is as though the contacting of gas and bed is sufficient to establish an equilibrium in the concentration of particles of a given size between the dense and dilute phases, and the dynamics of the process is practically irrelevant (just as knowledge of reaction rates is immaterial in chemical reaction when the reaction goes virtually to equilibrium).

A further very important example of this kind occurs in

the case of unburned carbon, closely related to combustion efficiency. A great amount of effort has been expended on studying the reaction of char particles, and the seemingly endless modification and variation in the design of experiments and the models resulting is both impressive and discouraging; will it never reach a satisfactory conclusion? The practical fact, however, seems to be that the major problem is in keeping fine char particles in the system long enough so that they may significantly burn, because small char particles are very rapidly transported out of the bed and elutriated. Thus the major unsolved problem in modelling char burning really lies in predicting the residence time of fine char particles in the bed, with and without recirculation. It seems significant that we have observed [Becker, et al. 1984] a very good correlation between carbon loss for a number of coals and a parameter involving bed particles size and fluidizing velocity in a combination like that in the aforementioned elutriation correlation. There is no evidence whatever that the fluidization dynamics need be well understood--or perhaps even invoked--to very well model carbon burnup.

My overall impression is that accurate treatment of fluidization dynamics and dilute-phase/dense-phase transfer processes is of relatively low importance to the satisfactory 1--D modelling of FBC. More work in this area would be helpful for improving detailed and accurate understanding of phenomena but is unlikely to contribute much to greater accuracy of prediction of the practically important performance parameters. Such work might, of course, allow stricter testing of these tentative conclusions. At present, however, it appears that effort would better be expended in areas of more serious ignorance and urgent need.

A second major problem in modelling coal burning, besides the difficulty with the residence-time distribution of fine char particles, occurs in the earlier stages of combustion and has

been rightly emphasized by Massimilla and coworkers [Chirone, et al. 1983]. This is the fragmentation and attrition of burning coal particles (or lumps), particularly in the larger sizes. These are not predictable from pure theory and it appears that bench-scale tests, at least, will always be needed to appropriately characterize a coal.

A final problem of coal burning which is in unsatisfactory condition for FBC is devolatilization. Instantaneous devolatilization has commonly been assumed (in a plane at the level of the distributor plate in underbed feeding, in a plane at the top of the bed in overbed feeding, or uniformly throughout the bed). It has been correctly pointed out that devolatilization of large coal particles is far from instantaneous. This problem is most important in overbed feeding, when the volatiles tend most strongly to burn in the freeboard. It is nevertheless hard to say whether better devolatilization models would notably improve the performance of a DPM model as a whole. More work is clearly needed. I have a feeling that an improvement would be obtained if (particularly with overbed feeding) a moderately good prediction could be made of the division of volatiles combustion between the freeboard and the bed. This division affects, among other things, the predicted bed temperature. However, it may not be possible to develop devolatilization models to this level of sophistication.

In summary, it is my belief, based on what I heard at the Seventh IEA Technical Committee Meeting in Italy and on my own experience and reading, that the most critical outstanding problems in the 1-D modelling of FBC are (in the order of decreasing importance):

1. The residence time distribution of elutriable char particles

2. The fragmentation and attrition of burning coal particles

3. The relatively slow devolatilization of large coal particles.

These problems share the characteristic that they are all in some way vital in the overall model, and knowledge of solutions is so far inadequate or, in the case of the first, totally lacking.

3.4 Three-dimensional effects

Following is a list of important 3--D effects in FBC.

1. Macro-circulation patterns in the bed solids. If, for example, the flow of dilute phase (bubbles, etc.) is more vigorous up the central region of the bed than the wall region, then a circulation of the dense phase will set in with upflow in the centre and downflow at the walls. Such circulation promotes bed turnover and solids mixing. Circulation patterns are affected by baffles, in-bed heat exchange tubes, other internals, and by non-uniform air distribution at the distributor. While such circulation is 3--D, it does not necessarily affect significantly the modelling of combustion and sulphur capture.

2. Volatile combustion. It is well established that when coal is fed underbed, devolatilization tends to be concentrated around feedpoints and volatile plumes are found to emanate from around those points. This is quite different from what is visualized in 1--D models. Allowance for such effects greatly complicates modelling, and it has not yet been demonstrated that predictions of performance parameters of principal interest would be significantly improved. The question, however, is certainly worth further study. Experimentally, these effects are a nuisance, greatly increasing the number of points from which gas samples must be drawn in order to get meaningful results.

3. Coal and limestone mixing. Vertical solids mixing in a

fluidized bed tends to be much faster than lateral solids mixing (vertical dispersion coefficients are an order of magnitude larger than horizontal coefficients). If coal and limestone feedpoints (particularly coal) are not located close enough together horizontally, then dead areas (in terms of combustion) tend to develop between feedpoints and process performance deteriorates. The problem here is, primarily, not how to model system performance in the presence of such effects, but how to avoid the effects by making sure that there is a sufficient density of feedpoints. This question has been studied experimentally and theoretically (using submodels for particle dispersion) and has led to the rule of at least one feedpoint per square meter bed. Because they are costly, it is attractive to have as few feedpoints as possible, so the problem bears examination whenever new systems are being developed. In overbed feeding, the problem of uniform feed distribution is fairly satisfactorily handled by use of spreader stokers.

4. Partial slumping. When a bed is partly slumped (typically as a means of dealing with low load), a not inconsiderable transition zone between the active and inactive regions may be created. Modelling of behaviour in such transition zones is expected to be useful in assessing strategies for slumping and refluidizing and identifying possible problems such as clinkering. Leckner and coworkers are studying this problem [Andersson 1983].

5. Spotty or unstable air distribution in large beds. Problems with uneven air distribution can arise with beds that are large in their horizontal dimensions relative to the bed height. The problem to be solved is primarily how to get a stable, uniform distribution, not how to model system performance with an non-uniform distribution.

6. Deliberately non-uniform air distribution (presumably to promote bed circulation, as in item 1).

7. Non-uniform heat removal in large beds. If water-cooled walls are used, for example, and the bed is large in both horizontal dimensions, the wall regions of the bed might be found running cold relative to the central region.

As may be seen from the above, some 3--D effects are essentially problems to be eliminated. Others are basically significant to general performance modelling under certain operating conditions and need to be dealt with.

4. Lumped parameter models

An extended discussion of lumped parameter modelling is not in order here; the methods by which "correlations" are developed from data are familiar to most scientists and engineers, and the usefulness of such correlations is also widely recognized. However, a few examples of significant correlations for FBC may be helpful. The following two are taken from our recent work at Queen's University, not because others have not contributed in this area but because they are fresh in my mind and still rather exciting. The discovery of strong elements of order and structure in a set of data is at once gratifying and challenging. The challenge is to physically explain the observed relationships.

The first example is a correlation of elutriation [Xu, et al. 1983] which shows that

$$\phi_D = \phi_D(D_p/v^{1.163},\ r), \qquad (1)$$

where ϕ_D is the mass fraction of particles of diameter D_p that is elutriated, $1 - \phi_D$ is the fraction leaving the bed as overflow, v is the fluidizing velocity, and r is the recycle fraction (the fraction of cyclone product that is recycled through the bed). This correlation describes very well indeed both cold model and FBC pilot plant results and is as remarkable

for what is not in it as for what is. Bed height, for example, is absent; it is unimportant. In-bed tubes are not mentioned; it appears that they have scant influence. This LPM was developed from experimental data. There is as yet no DPM (submodel or integrative) that can adequately generate such data.

The second example [Becker, et al. 1983] is a correlation of overhead carbon loss (via cyclone and baghouse product):

$$\dot{m}_{C,o} = 0.000335\ \dot{m}_{C,f}(v^{1.163}/\hat{D}_p)^{0.74}\ \phi_a^{-0.05}\ \cdot$$

$$\cdot\ \exp(-0.36\ r)\ \exp(5200/T_b) \qquad (2)$$

where $\dot{m}_{C,o}$ is the overhead carbon loss rate, kg/hr; $\dot{m}_{C,f}$ is the carbon feedrate (via the coal), kg/hr; $\hat{D}_p$ is the mean bed-particle diameter, m; ϕ_a is the theoretical air ratio (air supplied/air required for combustion); T_b is the bed temperature, K; and the other variables are as in eq. (1). The occurrence of the ratio $v^{1.163}/D_p$ both here and in eq. (1) is significant and plainly indicates the strong role of elutriation in overhead carbon loss. The factor $\exp(5200/T_b)$ indicates importance of kinetics, which is reasonable since the particles elutriated are the small ones.

It will be observed that correlations such as eqs. (1) and (2) indicate simply and clearly the effects of changes in operating conditions (feedrates, fluidizing velocity, bed particle size, bed temperature, etc.). Distributed parameter modelling, which generates only numbers and application of which is computationally immensely more complex and time-consuming, is relatively unrevealing. This is especially critical in applications such as computer control of the FBC process. I am convinced that there is a real need not to stop, and be satisfied, with generating data by experiment and by DPM modelling, but to go on to critically and imaginatively analyze such data to uncover the regularities and trends and to describe these features in terms of practically useful correlations.

5. Conclusions and recommendations

5.1 Introduction

The preceding discussion has given a view of the objectives and present status of mathematical modelling of FBC, on the basis of which I shall now address the two principal items in the fifth task specified in the contract Statement of Work:

- an assessment of the near-term potential mathematical modelling is likely to have as a cost-effective tool in designing commercial fluidized-bed combustors and boilers

- a reasoned recommendation as to whether Canadian participation in any further joint project on mathematical modelling of fluidized bed combustion is likely to be justified in terms of benefits to Canadian suppliers and users of the technology.

I again distinguish between:

- distributed-parameter models (DPM's) which are based on the governing integro-differential equations and a host of more or less detailed and usually mechanistic submodels which describe various aspects of the material properties, thermodynamic properties, transport phenomena, and chemical reaction phenomena

- lumped-parameter models which are typically correlations of data generated by physical experimentation and/or DPM modelling (experimental data may be obtained from bench-scale systems, pilot plants, demonstration plants, and full operating plants).

5.2 Assessment of near-term potential

It is my considered opinion that mathematical modelling

of FBC several years ago passed the point beyond which there can be no doubt of its value as a cost-effective tool in designing commercial fluidized-bed combustors and boilers. However, this view must still be qualified with explanations and conditions:

1. It can be effective only if one or more influential persons involved in a design are duly qualified; to wit:

- proficient in computer simulation
- well acquainted with FBC simulation models and submodels
- conversant with the FBC literature
- possessed of good engineering judgment.

In short, there is need for good people with a thorough background and skills in FBC modelling.

2. Modelling of FBC as a whole is at the stage where the designer who understands it has a great advantage over one who does not. The former presumably works at the limit of current understanding, with corresponding finesse and an informed sense of optimality. Further, when the plant has been built and the time comes for working out the bugs, he has a great advantage as a diagnostician in that he is best able to interpret the symptoms and formulate appropriate corrective action. The latter, on the other hand, unable to appreciate with any depth what is going on, will try to muddle through. Working with a process as complex as FBC, he is almost certain to end up well off-optimum in many respects and may in some be disasterously wide of the mark. Further, as a diagnostician, he is far more likely to fumble, playing dice with the inputs and acting on mistaken conclusions.

3. Modelling of FBC is not yet at the stage where it can accurately answer all interesting questions. Many of the

submodels in DPM modelling need considerably more research. Some of the problems, because of experimental difficulties or (for theory) excessive complexity, may never be satisfactorily solved. The present state is that modelling, intelligently used, provides a very powerful aid to design which most definitely should not be ignored but which cannot yet give all the answers. We cannot yet program models into a computer, enter in the parameters for a proposed boiler or combustor, and have it spew out a design.

4. Every effort should be made to translate experimental data and (from DPM's) computer-generated data into LPM's that can easily be used for design, control, operation, diagnostics, etc. An excellent example is the case of heat transfer coefficients between bed and in-bed tubes. Extensive experimental work has been done and detailed mechanistic models have been developed. Happily all these results have been collapsed into reasonably good correlations (LPM's) for the designer and other users; see, for example, the equation of Glicksman and Decker [1980]. It may be observed, too, that no designer of any account would proceed by simply guessing heat transfer coefficients if he could possibly do better. The value of modelling, particularly LPM modelling, is of unquestionable value on this issue and on many others in FBC. The purpose of models is clearly to take the guesswork out of design by putting science (which is expressed through models) in.

5. I return to the thought begun in the first numbered paragraph above. If FBC and a capacity for designing and best using FBC systems are indeed important to Canada, then a strong effort should be made to promote appropriate training and employment of manpower. People who have been adequately trained and indoctrinated in FBC applied science (which is a broader way of saying modelling) are very necessary for the full and effective application and exploitation of that science. Consider, by way of example, the general field of combustors, furnaces and boilers. Very powerful computer modelling methods

for predicting radiative and convective heat transfer and many aspects of combustion performance have been available for some time now. However, these engineering tools have been exploited only where proficient people were available and influential. I have been hugely impressed, for instance, with the achievements in industry of graduates of the Ijmuiden Research Station of the International Research Foundation. The industry as a whole, however, is conservative and cautious, and continues to inefficiently and foolishly muddle on, banking too much on guesswork and tradition, producing non-optimum systems, often surprized and befuddled by scaleup and control problems, etc. A major problem for the application of FBC modelling in the short term might clearly be a lack of people able to do the job. This is a top-priority consideration.

5.3 Recommendations for Canadian participation in IEA joint projects

Given the great range of possible cooperative projects and associated costs, I cannot offer any flat and simple recommendation. Instead, the possibilities have to be identified and weighed and the critical question put for each, "Is this activity likely to be justified in terms of the benefits to Canadian suppliers and users of the technology?" In some cases cooperation costs virtually nothing, so why deny it; in some the problems are "motherhood issues", in some there is genuine controversy, and in some there may indeed be no likely profit to Canada. Following is a list of possibilities raised at the 7th meeting of the IEA Committee, with related practical considerations and recommendations for Canadian response:

1. Sharing ideas. An obviously good policy for parties looking for mutual benefit from cooperation. Requires trust and a healthy willingness to share credit. Dollar cost is small, possible benefits considerable. Canadian participation is recommended with the reservation that any idea having the potential of producing a significant patent should be duly protected.

2. Sharing plans, experimental designs. Presumably this means trading usefully detailed information about future activities, hopefully far enough in advance to allow constructive criticism and suggestions. Same comments as for item 1; participation recommended.

3. Sharing data. Requires good planning and organization. Desirably there should be agreement on exactly what data are to be provided, in what format, and so forth. Provides opportunity for testing models against results for different systems. Dollar cost would be low. Canadian participation recommended.

4. Meetings to exchange information. These would presumably be special meetings beyond the present technical meetings of the Committee. The purpose would be to accomplish something substantially beyond what can be done by mail or at the normal technical meetings. There would have to be an agreed upon agenda and thorough preparation. Since travel costs are not inconsiderable, expense is a factor. There is also a considerable investment of time. Canadian participation in any such meeting should probably be conditional on the meeting being deemed important enough to justify the cost.

5. Joint work in certain areas, such as instrumentation. I am not opposed in principle and might be very enthusiastic about a suitable project. However, I recommend against any blanket commitment; consideration should be on the basis of specific proposals. Costs might be high, necessitating cost/benefit analysis.

6. Exchange of personnel. This also should be dealt with on the basis of specific proposals. Mutual benefits would have to outweigh costs. The possibility should certainly be kept in mind, and there might be cases from time to time where knowledge or skills can best be acquired by this route.

7. Cooperation in a specific project. I presume this might be something like everyone using the same coal and limestone and following an agreed-upon experimental plan for a set of trials. Thorough planning and coordination would be required. The cost is likely to be high. Canadian participation should be based on evaluation of specific proposals.

8. Develop a common DPM model, with participants dividing the sharpening of various submodels. This sounds like a fine thing to attempt, but it should be approached with due caution and reflection. Poorly managed, it could end as a great waste of time and money. I recommend that any move in this direction be started with a two-day planning and discussion meeting. The meeting itself should be very well organized and thoroughly prepared for by all concerned. The meeting would include:

- ☐ a review of existing modelling schemes, identifying and assessing integrative models and submodels
- ☐ a decision on which submodels are in good shape and which require more work
- ☐ agreement on an integrative 1--D model
- ☐ a discussion of what needs to be done on the deficient submodels
- ☐ a discussion of 3--D effects and what to do about them
- ☐ a division of work to be done on submodels
- ☐ assignment of responsibility for management of the integrative model
- ☐ agreement on goals

- organization and time-planning of the work

Canadian representatives should attend such a meeting. Continued participation in the exercise would, I believe, have to be conditional on a favourable cost/benefit analysis. The commitment of resources would presumably be high. If well organized and smartly executed, such a project--the development of an "IEA Model"--could greatly stimulate the research of the participants and produce very useful results. The exercise of developing the model could also be a very valuable learning and training experience.

In short, Canada should, I am sure, approach joint projects with an open but normally critical mind. International collaboration in affairs like this is clearly not an end in itself. The end for Canada is results that are useful and cost-effective to Canada. The hope is that collaboration will produce better results for Canada and for every other participating nation, and more economically and quickly, than can be obtained by independent effort. Whether or not this may happen can only be judged by evaluating specific proposals. It is necessary, also, to insist on thorough preparation and organization.

The above discussion, except on item 8, is lacking in specific examples of useful cooperative effort. I shall conclude by listing some that seem worthy of consideration and in line with the spirit of the discussion at the IEA Committee meeting:

- testing DPM submodels and/or LPM models against experimental data from the various systems of the participants. This would allow critical evaluation of the model, finer adjustment and calibration, broader variation of parameters, more rigorous testing of generality, identification and characterization of system-specific features, etc. Each participant would examine the application of the model to

his data, with (normally) the instigator acting as coordinator. The exercise may involve extra work in that some participants may not normally collect the required data. From our own work, for example, I would greatly like to see how the correlations cited in Sect. 4 (eqs. 1 and 2) fit data on other systems.

- testing effects of operating parameters that are inflexible or hard to change in a given system. One participant may have an extra high freeboard, another a large bed area, another a different configuration of in-bed cooling surfaces, another a specially interesting recycle system, etc. It would likely be desirable to carry out trials with the same coal and limestone, so some shipping of materials would be involved.

- most or all participants who have suitable systems carrying out a set of trials with specified coal(s) and limestone(s) to develop/test/refine a specified set of models. This would be costly and time-consuming and would need careful consideration. One should start by comparing the various systems to determine the similarities and differences. An overall experimental design should be followed which optimally exploits the capabilities of the participants and their systems.

- It is worth mentioning that there are various possibilities for mutual help that do not directly involve cooperation in mathematical modelling but that are nevertheless supportive. Primarily this involves participants putting at each others service, when it is reasonable to do so, any special testing, analytical, etc. capabilities in their possession. One may have a special bench-scale system for evaluating limestones. Another may have especially good systems for characterizing fine particles. Some may find it useful to get results from other laboratories to check their chemical analyses. It is

obviously important to know each others capabilities.

References

Note: the specification "IEA Committee Meeting, Italy" identifies a paper presented at the Special Session on Mathematical Modelling, 7th Combined Technical and Executive Committee Meeting, IEA Agreement on Atmospheric Fluidized Bed Combustion, Naples, October 6, 1983.

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